Appendix B
Detailed Cathodic Protection Design Procedures for Pike Island Auxiliary Lock Gates

DESIGNS FOR LOCK GATES

Figure B1 shows a Pike Island auxiliary miter gate. This gate is approximately 18.85 m (62 ft) long and 10.64 m (35 ft) high. With the river at normal water level, portions of each gate will always be submerged, and other portions may be submerged or exposed as lockages occur. During times of high water, more gate surfaces will be submerged, and, under conditions of flood, the entire gates may be submerged. The usual water depth is 9.12 m (30 ft).

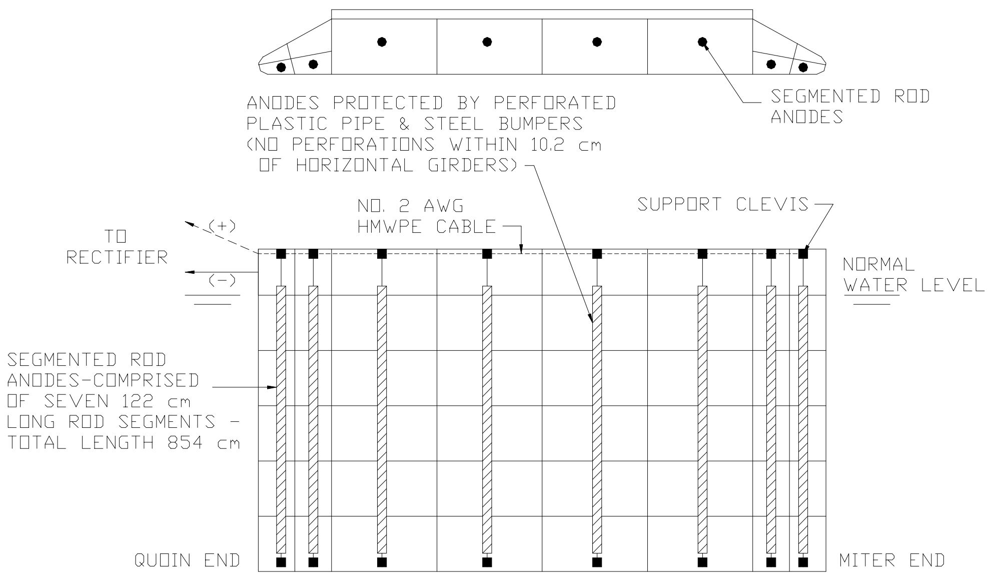

Figure B1. Pike Island auxiliary lock miter gate

The gates are constructed of welded structural steel, horizontally framed, with a cast pintle. The downstream side of the gate consists of a pattern of rectangular chambers closed on five faces and open to the water on the sixth face. The upstream face of the gate is made up of a large skin plate over the major portion of the face and two columns of small chambers at the quoin and miter ends of the gate.

The main (large) chambers on the downstream face of the gate are set in four columns and are approximately 3.66 m (12 ft) wide, varying in height from 1.01 m (3 ft 4 in.) to 1.82 m (6 ft), with a depth of 1.06 m (3 ft 6 in.). The two sets of vertically aligned chambers, at the quoin and miter ends of the gates, are much smaller and irregularly shaped. There are 6 horizontally aligned rows of chambers placed one above the other in each vertical column, giving a total of 48 chambers on the downstream side.

Design Data

a. The lock is located in fresh water with a resistivity of 3000 ohm-centimeters.

b. Water velocity is less than 1524 mm/s (5 ft/s).

c. Water contains debris, and icing will occur in the winter.

d. The gate surfaces have a new vinyl paint coating, minimum of 0.15 mm (6 mils) thick, with not more than 1 percent of the area bare because of holidays in the coating.

e. The coating will deteriorate significantly in 20 years of exposure. Experience shows that 30 percent of the area will become bare in 20 years.

f. Design for 75.35 mA/m^2 (7.0 mA/ft^2) (moving fresh water).

g. Electric power is available at 120/240 volts AC, single phase at the lock site.

h. Design for a 20-year life.

i. Design for entire surface of the gate to be submerged.

j. Base anode requirement on the average current requirement over the anode design life.

k. Base rectifier requirement on maximum (final) current requirement at end of anode design life.

Computations

1) Find the surface area to be protected.

A) Upstream side

Area of skin plate: 14.51 m x 10.67 m = 154.82 m^2 (1666 ft^2)

Chamber areas at each end (same at each end):
6 chambers @ 6.50 m^2 = 39.02 m^2 (420 ft^2)
6 chambers @ 3.72 m^2 = 22.30 m^2 (240 ft^2)
6 chambers in each vertical column

B) Downstream side

Number of Chambers	Chamber Area m^2 (ft^2)	Total Area m^2 (ft^2)
4	5.85 (63)	23.41 (252)
4	6.60 (71)	26.34 (284)
4	7.06 (76)	28.24 (304)
4	8.08 (87)	32.33 (348)
4	8.55 (92)	34.19 (368)
4	13.47 (145)	53.88 (580)
4	14.68 (158)	58.71 (632)
4	15.51 (167)	62.06 (668)
4	16.63 (179)	66.52 (716)
2	17.28 (186)	34.56 (372)
4	18.12 (195)	72.46 (780)
2	19.14 (206)	38.28 (412)
2	21.18 (228)	42.36 (456)
2	22.20 (239)	44.40 (478)
Total number of chambers = 48 Total chamber area = 194.17 m^2 (2092 ft^2) Total area = 617.81 m^2 (6650 ft^2)		

2) Calculate the current requirements (I) from Equation 1.

$$I = A * I'(1.0 - C_E) \quad [EQ\ 1]$$

where

A = surface area to be protected (varies depending on portion of structure)

I' = required current density to adequately protect gate 75.35 mA/m^2

C_E = coating efficiency (0.99 initial, and 0.70 final)

A) Upstream side

Skin plate current requirement

Calculate I

where A = 154.82 m^2 (1666 ft^2) (from computation step 1A).

Initial current requirement (C_E = 99%):

I = 154.82 m^2 x 75.35 mA/m^2 x (1 - 0.99) = 116 mA (use 120 mA)

Final current requirement (C_E = 70%):

I = 154.82 m^2 x 75.35 mA/m^2 x (1 - 0.70) = 3498 mA (use 3500mA)

Average current requirement:

I = (120 + 3500)/2 mA = 1810 mA (use step 2A for skin plate)

End chamber current requirement

To be able to use the same anode assembly in each set of chambers, base the design on the larger of the two chambers at each end.

Calculate I

where A = 39.02 m^2 (420 ft^2) (from computation step 1A).

Initial current requirement (C_E = 99%):

I = 39.02 m^2 x 75.35 mA/m^2 x (1 - 0.99) = 29.4 mA (use 30 mA for 6 chambers)

Final current requirement (C_E = 70%):

I = 39.02 m^2 x 75.35 mA/m^2 x (1 - 0.70) = 882 mA (use 900 mA per 6 chambers)

Average current requirement:

I = (30 + 900)/2 = 465 mA per 6 chambers (use 0.5 per 6 chambers in a vertical column).

This is current requirement for one vertical column of 6 chambers. Total average current requirement is four times this amount:

I = 0.5 x 4 = 2.0 A for chamber

Total current requirement (I_T) for upstream side:

I_T = 120 mA + (4 x 30 mA) = 240 mA = 0.24 amps (initial)
I_T = 2.0 A + 2.0 A = 4.0 amperes (average)
I_T = 3500 mA + (4 x 900 mA) = 7100 mA = 7.10 amps (final)

B) Downstream side

Calculate I

where A = 22.20 m^2 (239 ft^2) (from computational step 1B).

Initial current requirement (C_E = 99%):

I = 22.20 m^2 x 75.35 mA/m^2 x (1 - 0.99) = 16.8 mA per chamber

Final current requirement (C_E = 70%):

I = 22.20 m^2 x 75.35 mA/m^2 x (1 - 0.70) = 502 mA per chamber

Average current requirement:

I = (16.8 + 502)/2 = 260 mA per chamber

Total current requirement for downstream side (48 chambers):

I_T = 16.8 mA/chamber x 48 chamber = 806 mA = 0.8 A (initial)
I_T = 260 mA/chamber x 48 chamber = 12,480 mA = 12.4 A (average)
I_T = 502 mA/chamber x 48 chamber = 224,096 mA = 24.2 A (final)

C) Total current requirement

Initial

Upstream side	= 0.24 amps
Downstream side	= 0.80 amps
	1.04 amps

Average

Upstream side	=	4.0 amps
Downstream side	=	12.4 amps
		16.4 amps

Final

Upstream side	=	7.1 amps
Downstream side	=	24.2 amps
		31.3 amps

Note: Average current requirements determine anode selection. Final current requirements determine rectifier selection.

3) Select the anode and calculate the number of anodes required (N) to meet the design life requirements.

Disk anodes such as those shown in Figure B2 are considered best for the skin plate on the upstream side. Either 3.2-mm- (1/8-in.-) diam segmented rod anodes consisting of 1,219-mm (4-ft) segments, as shown in Figure B3, or continuous 3.2-mm- (1/8-in.-) diam prefabricated rod anodes are considered best for the chambers.

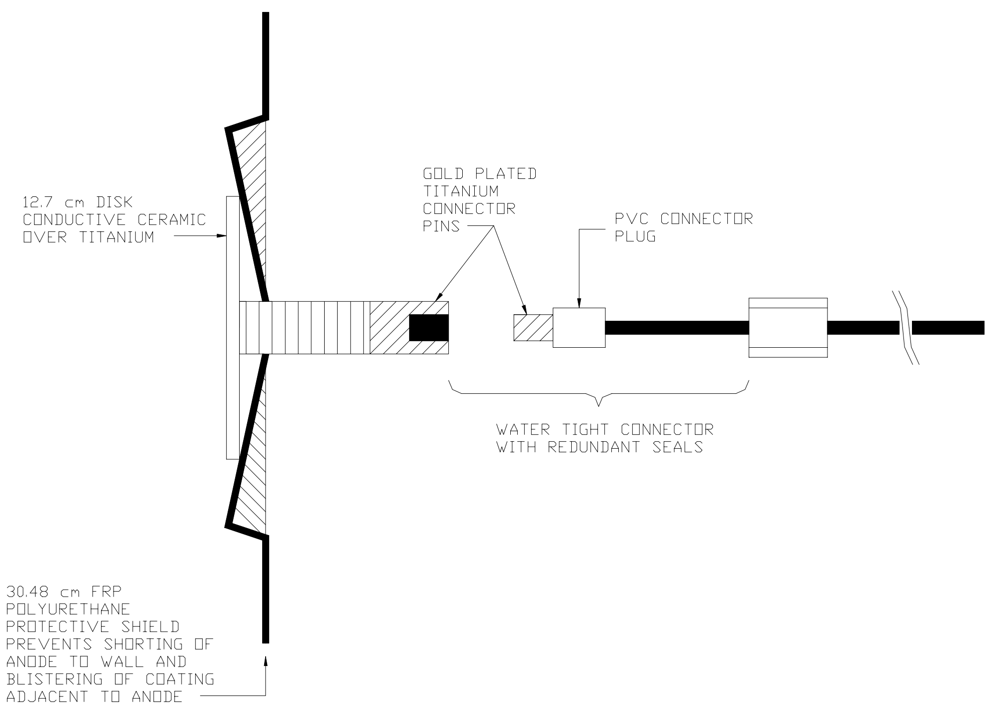

Figure B2. Typical ceramic-coated flat disk anode

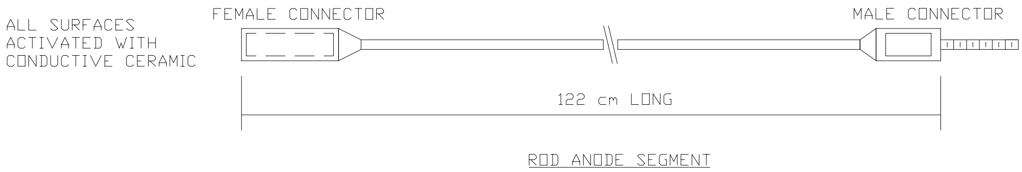

Figure B3. Typical ceramic-coated rod anode design

For this example, the design based on the 1219-mm (4-ft) segments. The design for the continuous rod material would be identical since they have the same amperage capacity per lineal foot of anode material. Number of anodes is calculated from Equation 2.

$$N = \frac{I}{I_A} \qquad \text{[EQ 2]}$$

where

I = total current requirement
I_A = average current per anode for the anode's desired life.

A) Upstream side

<u>Skin plate - number of disk anodes</u>

Calculate N

where I = 2 A (from step 2A)
I_A = 0.84 A/disk anode

$$N = \frac{2}{0.84} = 2.4 \text{ anodes; use 3 disk anodes}$$

<u>Chambers - number of segmented rod anodes</u>

For each set of 6 chambers in a vertical column

Calculate N

where I = 0.5 A (from step 2A)
I_A = 1.0 A/1219-mm- (4-ft-) long segmented rod (from Table B-1M (Metric)/B-1 (U.S. Customary))

$$N = \frac{0.5}{1} = 0.5 \text{ anodes; use 1 segmented rod anode per 6 vertical chambers}$$

B) Downstream side

I = 260 mA per chamber

For each set of 6 chambers in a vertical column

I = 6 x 260 mA = 1560 mA = 1.56A
I_A = 1.0 A/anode (from Table B-1M/B-1)

$$N = \frac{1.56}{1} = 1.56 \text{ anodes; use 2 segmented rod anodes per 6 vertical chambers}$$

<u>4) Select number of anodes to provide adequate current distribution.</u>

A) Upstream side

Skin plate

Experience shows that an anode grid spacing of 3.048 to 3.658 m (10 to 12 ft) provides adequate coverage of protective current. Additional anodes are also needed along the bottom of the gate, as this is an area where coating damage occurs readily, thus exposing an appreciable amount of bare metal. Figure B4 shows a suitable configuration using a combination of 19 disk anodes.

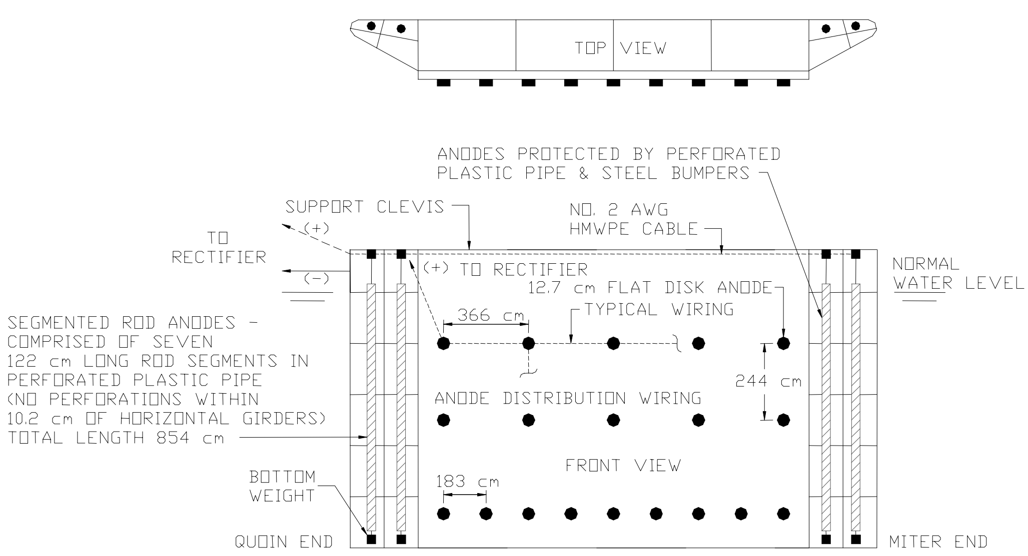

Figure B4. Auxiliary lock miter gate design at Pike Island

Table **B-1M (Metric)**
Dimensions and Ratings of Ceramic Anodes
Underground Usage

Wire and Rod Anodes (Packaged)

Anode Element Dimension mm x mm	Package Size mm	Weight kg	Current Rating, amps				
			10-Year Design Life	15-Year Design Life		20-Year Design Life	
			HDC	HDC	SC	HDC	SC
3.2 x 610	51 x 762	13.22	1.3	1.10	0.6	0.9	0.5
1.6 x 1524	51 x 1829	30.86	1.5	1.25	0.7	1.0	0.6
1.6 x 1524	76 x 1829	57.32	1.5	1.25	0.7	1.0	0.6
3.2 x 1219	51 x 1524	26.45	2.7	2.2	1.2	1.8	1.0
3.2 x 1219	76 x 1524	48.50	2.7	2.2	1.2	1.8	1.0
6.4 x 1219	76 x 1524	48.50	5.5	4.4	2.4	3.5	2.0
3.2 x 1829	76 x 2438	77.16	4.0	3.3	1.8	2.7	1.5
9.5 x 1219	76 x 1524	48.50	7.5	6.0	3.6	5.1	3.0
12.7 x 1219	76 x 1524	50.70	10.0	8.0	4.8	6.8	4.0
19 x 1219	76 x 1524	55.11	15.0	12.0	7.2	10.0	6.0
3.2 x 1829	76 x 2438	77.16	4.0	3.3	1.8	2.7	1.5
6.4 x 1829	76 x 2438	77.16	8.2	6.6	3.6	5.3	3.0
3.2 x 2438	76 x 3048	97.00	5.4	4.4	2.4	3.6	2.0
6.4 x 2438	76 x 3048	97.00	11.0	8.8	4.8	7.0	4.0

Note: HDC = heavy duty coating tubular anodes (in coke breeze).
SC = standard coating tubular anodes (in coke breeze).

Anode Element Dimension, mm x mm	20-Year Design Life Current Rating, amps
25.4 x 250	2.00
25.4 x 500	4.00
25.4 x 1000	8.00
16 x 250	1.25
16 x 500	2.50
16 x 1000	5.00

Table B-1M (Cont'd)
Fresh and Seawater Usage

Wire and Rod Anodes (Bare)

Life (years)	Fresh Water	Brackish Water	Seawater
Maximum Current(A)/305-mm Length for 20-Year Design Life of 1.6-mm-diam Wire			
10	0.39	0.51	0.85
15	0.31	0.44	0.74
20	0.26	0.39	0.67
Maximum Current(A)/305-mm Length for 20-Year Design Life of 3.2-mm-diam Rod or Wire			
10	0.79	1.02	1.7
15	0.62	0.88	1.47
20	0.52	0.79	1.33
Maximum Current(A)/305-mm Length for 20-Year Design Life of 6.4-mm-diam Rod			
10	1.58	2.04	3.41
15	1.24	1.76	2.95
20	1.04	1.58	2.66
Maximum Current(A)/305-mm Length for 20-Year Design Life of 8.3-mm-diam Rod			
10	2.37	3.06	5.11
15	1.85	2.63	4.42
20	1.56	2.37	3.99
Maximum Current(A)/305-mm Length for 20-Year Design Life of 12.7-mm-diam Rod			
10	3.16	4.08	6.81
15	2.47	3.51	5.9
20	2.08	3.16	5.33
Maximum Current(A)/305-mm Length for 20-Year Design Life of 15.9-mm-diam Rod			
10	3.95	5.1	8.52
15	3.09	4.39	7.37
20	2.6	3.95	6.66
Maximum Current(A)/305-mm Length for 20-Year Design Life of 19-mm-diam Rod			
10	4.74	6.12	10.22
15	3.71	5.27	8.85
20	3.12	4.74	7.99

Table B-1M (Cont'd)
Fresh and Seawater Usage

Tubular Anodes (Bare)

Seawater - Current in amps per anode (15-year design life)	
25.4 mm x 500 mm 25.4 mm x 1000 mm 16 mm x 500 mm 16 mm x 1000 mm	25 amps 50 amps 15 amps 30 amps
Sea Mud - Current in amps per anode (20-year design life)	
25.4 mm x 500 mm 25.4 mm x 1000 mm	6 amps 12 amps
Fresh Water - Current in amps per anode (20-year design life)	
25.4 mm x 500 mm 25.4 mm x 1000 mm 16 mm x 500 mm 16 mm x 1000 mm	4.00 amps 8.00 amps 2.50 amps 5.00 amps

Current Density Limitations

Wire and Rod Anode
Anode Life Versus Maximum Current Density (amps per 0.0929 m^2)

Life, years	Coke	Fresh Water	Brackish Water	Seawater
10	19	24	31	52
15	15	19	27	45
20	13	16	24	41

Tubular Anodes
Anode Life Versus Maximum Current Density (amps per 0.0929 m^2)

Life, years	Fresh Water	Brackish Water	Seawater
20	9.3	9.3	56

Table B-1M (Concluded)

Disk Anodes (see Figure B2)

Size: 127 mm diam (typical - other sizes available) Active Area: 12,258 mm^2 Weight: 907 g		
	Fresh Water	Salt Water
Current capacity - 20-year life (amps/anode)	0.84	5.00
Operating voltage - 20-year life (V)	20.0	10.0

Segmented Rod Anodes (see Figure B3)

Size: 1219-mm length; 3.5-mm diam Active Area: 14,194 mm^2 Weight: 65 g		
	Fresh Water	Salt Water
Current capacity - 20-year life (amps/anode)*	1.00	2.50
Operating voltage - 20-year life (V)	50.0	10.0

*Standard coating

Table **B-1(U.S. Customary)**
Dimensions and Ratings of Ceramic Anodes
Underground Usage

Wire and Rod Anodes (Packaged)

Anode Element Dimension	Package Size, in.	Weight lb	Current Rating, amps				
			10-Year Design Life	15-Year Design Life		20-Year Design Life	
			HDC	HDC	SC	HDC	SC
1/8 " x 2'	2 x 30	6	1.3	1.10	0.6	0.9	0.5
1/16" x 5'	2 x 72	14	1.5	1.25	0.7	1.0	0.6
1/16" x 5'	3 x 72	26	1.5	1.25	0.7	1.0	0.6
1/8" x 4'	2 x 60	12	2.7	2.2	1.2	1.8	1.0
1/8" x 4'	3 x 60	22	2.7	2.2	1.2	1.8	1.0
1/4" x 4'	3 x 60	22	5.5	4.4	2.4	3.5	2.0
1/8" x 6'	3 x 96	35	4.0	3.3	1.8	2.7	1.5
3/8" x 4'	3 x 60	22	7.5	6.0	3.6	5.1	3.0
1/2" x 4'	3 x 60	23	10.0	8.0	4.8	6.8	4.0
3/4" x 4'	3 x 60	25	15.0	12.0	7.2	10.0	6.0
1/8" x 6'	3 x 96	35	4.0	3.3	1.8	2.7	1.5
1/4" x 6'	3 x 96	35	8.2	6.6	3.6	5.3	3.0
1/8" x 8'	3 x 120	44	5.4	4.4	2.4	3.6	2.0
1/4" x 8'	3 x 120	44	11.0	8.8	4.8	7.0	4.0

Note: HDC = heavy duty coating tubular anodes (in coke breeze).
SC = standard coating tubular anodes (in coke breeze).

Anode Element Dimension	20-Year Design Life Current Rating, amps
1" x 9.8"	2.00
1" x 19.7"	4.00
1 " x 39.4"	8.00
0.63" x 9.8"	1.25
0.63" x 19.7"	2.50
0.63" x 39.4"	5.00

Table B-1 (Cont'd)
Fresh and Seawater Usage

Wire and Rod Anodes (Bare)

Life (years)	Fresh Water	Brackish Water	Seawater
Maximum Current/l-ft Length for 20-Year Design Life of .0625-in.-diam Wire			
10	0.39	0.51	0.85
15	0.31	0.44	0.74
20	0.26	0.39	0.67
Maximum Current/l-ft Length for 20-Year Design Life of .125-in.-diam Rod or Wire			
10	0.79	1.02	1.7
15	0.62	0.88	1.47
20	0.52	0.79	1.33
Maximum Current/l-ft Length for 20-Year Design Life of .25-in.-diam Rod			
10	1.58	2.04	3.41
15	1.24	1.76	2.95
20	1.04	1.58	2.66
Maximum Current/l-ft Length for 20-Year Design Life of .325-in.-diam Rod			
10	2.37	3.06	5.11
15	1.85	2.63	4.42
20	1.56	2.37	3.99
Maximum Current/l-ft Length for 20-Year Design Life of .5-in.-diam Rod			
10	3.16	4.08	6.81
15	2.47	3.51	5.9
20	2.08	3.16	5.33
Maximum Current/l-ft Length for 20-Year Design Life of .625-in.-diam Rod			
10	3.95	5.1	8.52
15	3.09	4.39	7.37
20	2.6	3.95	6.66
Maximum Current/l-ft Length for 20-Year Design Life of .75-in.-diam Rod			
10	4.74	6.12	10.22
15	3.71	5.27	8.85
20	3.12	4.74	7.99

Table B-1 (Cont'd)
Fresh and Seawater Usage

Tubular Anodes (Bare)

Seawater - Current in amps per anode (15-year design life)	
1 in. x 19.7 in. 1 in. x 39.4 in. 0.63 in. x 19.7 in. 0.63 in. x 39.4 in.	25 amps 50 amps 15 amps 30 amps
Sea Mud - Current in amps per anode (20-year design life)	
1 in. x 19.7 in. 1 in. x 39.4 in.	6 amps 12 amps
Fresh Water - Current in amps per anode (20-year design life)	
1 in. x 19.7 in. 1 in. x 39.4 in. 0.63 in. x 19.7 in. 0.63 in. x 39.4 in.	4.00 amps 8.00 amps 2.50 amps 5.00 amps

Current Density Limitations

Wire and Rod Anode
Anode Life Versus Maximum Current Density (amps/sq ft)

Life, years	Coke	Fresh Water	Brackish Water	Seawater
10	19	24	31	52
15	15	19	27	45
20	13	16	24	41

*Tubular Anode*s
Anode Life Versus Maximum Current Density (amps/sq ft)

Life, years	Fresh Water	Brackish Water	Seawater
20	9.3	9.3	56

Table B-1 (Concluded)

Disk Anodes (see Figure B2)

Size: 5-in. diam (typical - other sizes available) Active Area: 19 sq in. Weight: 2.0 lb		
	Fresh Water	Salt Water
Current capacity - 20-year life (amps/anode)	0.84	5.00
Operating voltage - 20-year life (V)	20.0	10.0

Segmented Rod Anodes (see Figure B3)

Size: 4-ft length; 0.138-in. diam Active Area: 22 sq in. Weight: 2.3 oz		
	Fresh Water	Salt Water
Current capacity - 20-year life (amps/anode)*	1.00	2.50
Operating voltage - 20-year life (V)	50.0	10.0

*Standard coating

Chambers

A continuous length of screw-coupled segmented rod anodes is needed for each chamber column at the miter and quoin ends extending from the high-water line down to within 610 mm (2 ft) of the bottom girder. Each anode consists of 7 segments, each 1219 mm (4 ft) in length. Four segmented rod anode assemblies are thus required, comprising a total of 28 segments, each 1219 mm (4 ft) in length. See Figure B5.

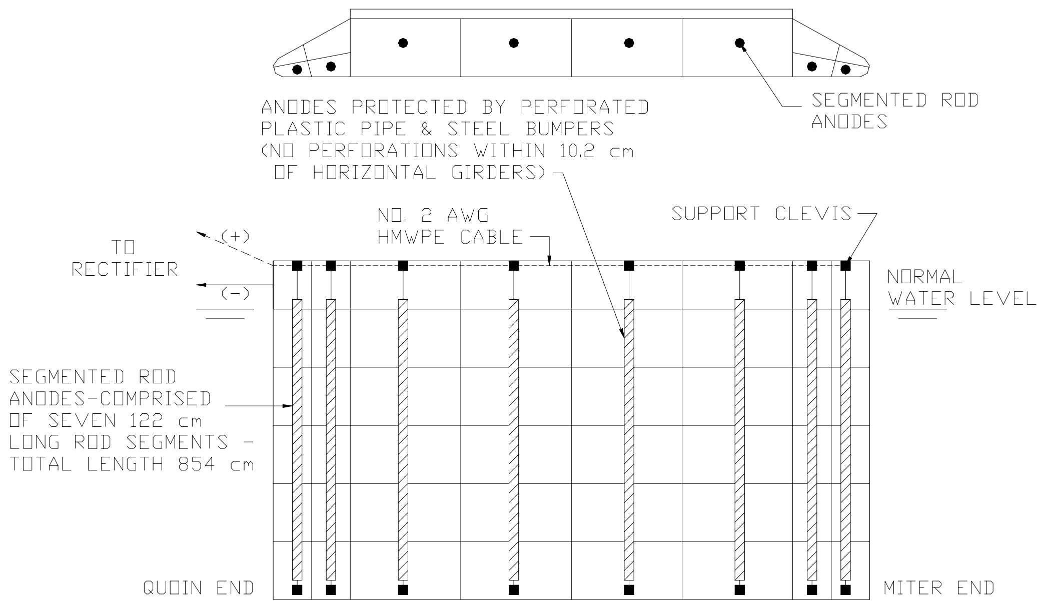

Figure B5. Auxiliary lock miter gate at Pike Island showing rod anode placement

Total anodes required for the upstream side:

19 disk anodes
4 segmented rod anodes (28 individual rod segments)

B) Downstream side

One continuous length of screw-coupled segmented rod anodes is needed for each chamber column extending from the high-water line down to within 610 mm (2 ft) of the bottom girder. (Note: For the downstream side of the downstream gates, a much shorter anode length will be required since only the lower portions of this gate surface are ever submerged.) Each anode rod consists of 7 segments, each 1219 mm (4 ft) in length. Eight segmented rod anodes are thus required, comprising a total of 56 segments, each 1219 mm (4 feet) in length. See Figure B5.

5) Determine the anode-to-water resistance (R_A) of the individual anodes.

Disk anodes

Empirical information indicates anode-to-water resistance (R_A) of a single 127-mm (5-in.) disk anode on a coated structure may be expressed by Equation 3.

$$R_A = \frac{p}{21.5} \qquad \text{[EQ 3]}$$

where p = 3000 ohm-cm (water resistivity from design item 1)
21.5 = Manufacturer correlation constant for 127-mm flat disk anode used to yield ohms

$$R_A = \frac{3000}{21.5} = 139.5\,\text{ohms}$$

The disk anode-to-water resistance (R_N) of the 19 disk anodes can be approximated from Equation 4.

$$R_N = R_A / N + (p * P_F) / C_C \qquad \text{[EQ 4]}$$

where:

R_A	=	139.5 ohms (disk anode-to-water resistance of individual disk anodes from previous calculation)
N	=	19 (number of anodes, design step 4)
p	=	3000 ohm-cm
P_F	=	0.0427 (paralleling factor from Table B-2M (metric)/B-2 (U.S. customary)
C_C	=	304.8 cm (10 ft) (center-to-center spacing of disc anodes).

R_N = 139.5/19 + (3000 x 0.0427)/(304.8 cm) = 7.7 ohms

At the maximum expected current of 3500 mA (3.5 amps), the voltage required for the disk anodes can be determined using Ohm's Law, Equation 5.

$$E = I \times R \qquad \text{[EQ 5]}$$

$$E = 3.5 \times 7.7 = 27 \text{ volts}$$

This is a reasonable voltage, so the 19 disk anodes are sufficient

<u>Segmented rod anodes</u>

The segmented rod anode-to-water resistance (RA) is calculated from Equation 6. the total length of anode is used, although a shorter length could be used if low water conditions were expected most of the time.

$$R_A = \frac{K \times p}{L} \times [\ln(8\,L/d) - 1] \qquad \text{[EQ 6]}$$

where p = 3000 ohm-cm (water resistivity from design item 1)
L = 853 cm (28 ft) (length of anode rod from design step 4)
d = 0.35 cm (0.0115 ft) (anode rod diameter)
K = 0.158 (metric)
K = 0.0052 (U.S. customary)

$$R_A = \frac{0.158 \times 3000}{853} \text{ x } \left(\ln \frac{8 \times 853}{0.35} - 1 \right)$$

$$R_A = 0.557 \ (9.88 - 1) = 4.95 \text{ ohms}$$

Table B-2M (Metric)
Anode Paralleling Factors for Various Number of
Anodes Installed in Parallel

N	P	N	P
2	0.0796	14	0.0512
3	0.0881	16	0.0472
4	0.0863	18	0.0442
5	0.0817	20	0.0411
6	0.0768	22	0.0390
7	0.0722	24	0.0369
8	0.0683	26	0.0347
9	0.0646	28	0.0332
10	0.0613	30	0.0317
12	0.0555		

Note: N = number of anodes; P = paralleling factors

Table B-2 (U.S. Customary)
Anode Paralleling Factors for Various Number of
Anodes Installed in Parallel

N	P	N	P
2	0.00261	14	0.00168
3	0.00289	16	0.00155
4	0.00283	18	0.00145
5	0.00268	20	0.00135
6	0.00252	22	0.00128
7	0.00237	24	0.00121
8	0.00224	26	0.00114
9	0.00212	28	0.00109
10	0.00201	30	0.00104
12	0.00182		

Note: N = number of anodes; P = paralleling factors

Voltage for upstream side rod anodes

At the maximum expected current requirement for the upstream chambers of 900 mA per vertical column of 6 chambers, the voltage required for each rod anode can be determined using Ohm's Law, Equation 5.

$$E = I \times R = 0.90 \text{ amps} \times 4.95 \text{ ohms} = 4.46 \text{ volts}$$

This is a reasonable voltage, so the single anode per column of chambers is sufficient.

Voltage for downstream side rod anodes

At the maximum expected current of 251 mA per chamber, the current required for one vertical column of 6 chambers is:

$$I = 6 \times 502 \text{ mA} = 3012 \text{ mA or } 3.0 \text{ amperes}$$

The voltage required for each anode is found using Equation 5:

$$E = I \times R = 3.0 \text{ amps} \times 4.95 \text{ ohms} = 14.9 \text{ volts}$$

This is a reasonable voltage, so the single anode per vertical column of chamber is sufficient.

6) Determine total circuit resistance (R_T) using Equation 7.

$$R_T = R_N + R_W + R_C \quad \text{[EQ 7]}$$

where: R_N = anode-to-water resistance
R_W = header cable/wire resistance
R_C = tank-to-water resistance

A) Upstream side

Skin Plate

R_N = 7.7 ohms (anode-to-water resistance)
R_W = 0.02 ohms (wire resistance)

R_w depends on the actual wiring of the anodes, but the general arrangement would be to use a header cable from the rectifier to the center of the disk anode array and then distribute the current through a junction box to each anode. Wiring would be in a conduit on the inside of the gate. Assuming the rectifier is 8.53 m (28 ft) from the gate, there will be about 30.48 m (100 ft) of positive and negative header cable. No. 2 AWG, HMWPE insulated cable is selected. The resistance of the anode distribution wiring is considered negligible. The header cable resistance is calculated from Equation 8.

$$R_W = \frac{L_W\, R_{MFT}}{1000} \qquad \text{[EQ 8]}$$

where L_W = 30.48 m (100 ft) (header cable length (as noted above))
R_{MFT} = 0.159 ohms (resistance per 304.8 m (1000 linear ft) of No. 2 AWG HMWPE)

$$R_W = \frac{30.48 \times 0.159}{304.8} = 0.016 \text{ ohms; use 0.02 ohms}$$

R_C = 0.00 ohms (structure-to-water resistance)

R_C is considered negligible since the design maximum capacity is based on a 30 percent bare structure which would have negligible resistance.

The total resistance R_T of the skin plate disk anode system using Equation 7 is:

$R_T = R_N + R_W + R_C = 7.7 + 0.02 + 0.0 = 7.72$ ohms

Chambers

Total resistance of the 4 upstream chamber anodes (R_N) is calculated as follows: The 4 anode rods are in parallel. Total resistance can be determined from the law of parallel circuits. Since all 4 anodes have the same anode-to-water resistance, the calculation becomes Equation 9.

$$R_N = R_A / N = 4.95 / 4 = 1.24 \text{ ohms} \qquad \text{[EQ 9]}$$

where: R_N = total resistance of all 4 anodes
R_A = 4.95 (anode-to-water resistance)
N = 4 (number of anodes)

R_W = 0.01 ohms (wire resistance)

R_W consists of a No. 2 AWG, HMWPE insulated cable. The rectifier will be located about 7.62 m (25 ft) from the gate, requiring 15.24 m (50 ft) of positive and negative header cable to the gate.

There will be about 18.29 m (60 ft) of cable on the gate. One half of the cable resistance is used in the calculation to allow for distribution of current.

Total wire length then is: 15.24 m + 9.14 m = 24.38 m (80 ft)

Resistance, R_W, is calculated from Equation 8:

$$R_W = \frac{L_W R_{MFT}}{1000} \qquad \text{[EQ 8]}$$

where: L_W = 24.38 m (80 ft) (header cable length (as noted above))
R_{MFT} = 0.159 ohms (resistance per 304.8 m (1000 linear ft) of No. 2 AWG HMWPE)

$$R_W = \frac{24.38 \times 0.159}{304.8} = 0.01\text{ohms}$$

R_C = 0.00 ohms (structure-to-water resistance is negligible)

Total resistance (R_T) of the upstream chamber system then from Equation 7:

$$R_T = R_N + R_W + R_C \qquad \text{[EQ 7]}$$

$$R_T = 1.24 + 0.01 + 0.0 = 1.25 \text{ ohms}$$

B) Downstream side

Calculations are similar to those from the upstream chambers. Anode-to-water resistance, R_N, from Equation 9 is:

$R_N = R_A/N$

where: R_A = 4.95 ohms (from design step 5).
N = 8 anode rods (from design step 3).

R_N = 4.95/8 = 0.62 ohms
R_W = 0.01 ohms wire resistance (wire length and resistance is the same as the upstream side).

Total resistance (R_T) from Equation 7:

$R_T = R_N + R_W + R_C$ = 0.62 + 0.01 + 0.0 = 0.63 ohms

<u>7) Determine required rectifier voltage (V_{REC}) and current.</u>

A) Upstream side

<u>Skin plate</u>

Maximum current required: 3.50 A (step 2A)
Resistance: 7.72 ohms (from step 6A)

Voltage required, Equation 5: E = I x R = 3.5 x 7.72 = 27 volts

<u>Chambers</u>

Maximum current required: 3.6 amperes (from step 2A)

Resistance: 7.72 ohms (from step 6A)

Voltage required, Equation 5: E = I x R = 3.6 x 1.25 = 4.5 volts

B) Downstream side

Maximum current required: 24.2 amperes (from step 2B)

Resistance: 0.63 ohms (from step 6B)

Voltage required, Equation 5: E = I x R = 24.2 x 0.63 = 15.3 volt

Selection of Rectifier

The largest design voltage requirement is 27 volts. Using a factor of safety of 120 percent, rectifier voltage is calculated:

27 volts x (120%) = 33 volts

Total current required:

Upstream skin plate	=	3.50 amperes
Upstream chambers	=	7.1 amperes
Downstream chambers	=	<u>24.2 amperes</u>
		34.8 amperes

For a commercially available rectifier having an output of 40 volts, 40 amperes is chosen. Because of the different circuit resistances, separate control over each circuit is required. This is best handled by a rectifier having 3 separate automatic constant current output circuits. Figure B6 shows the circuitry.

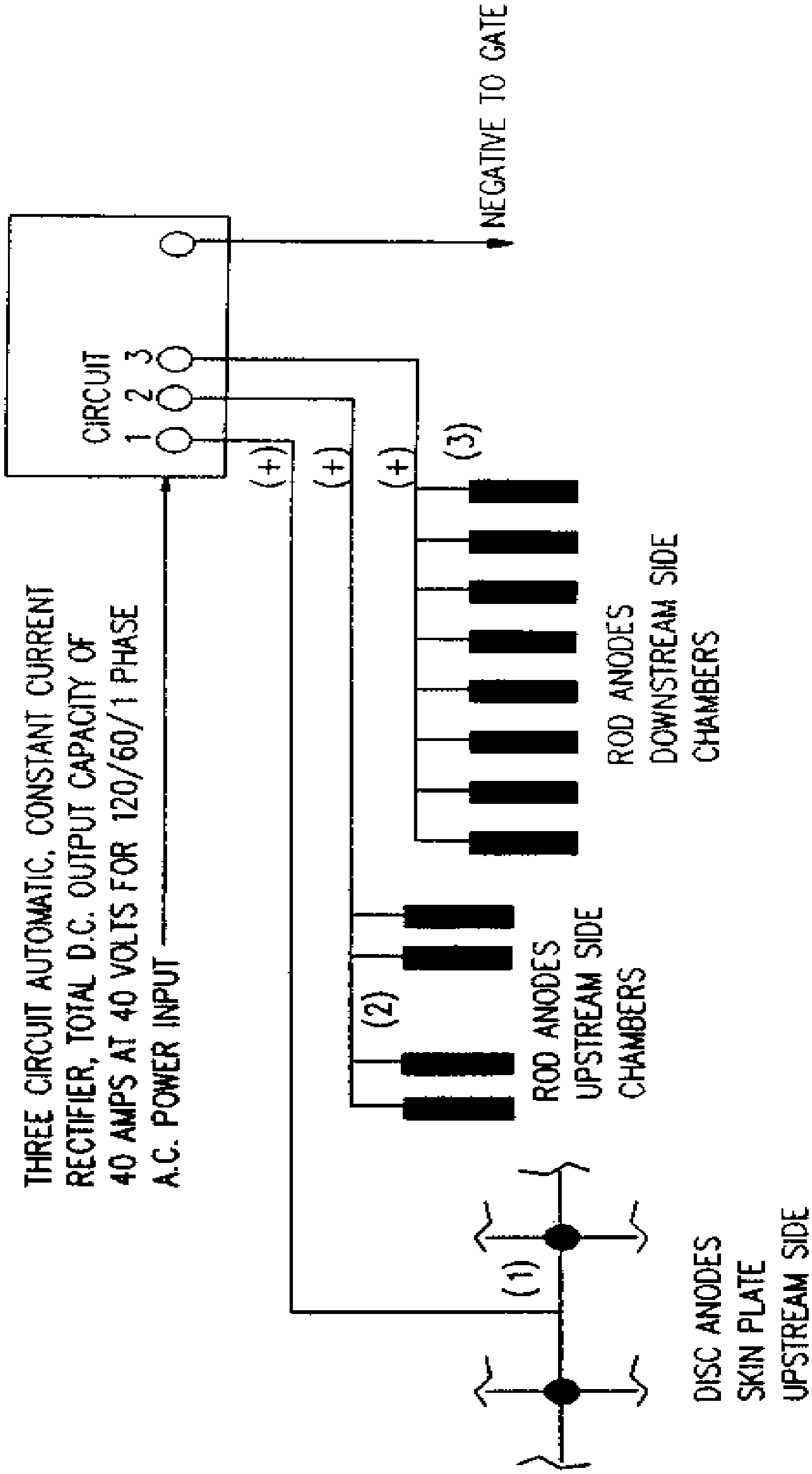

Figure B6. Circuit diagram lock miter gate

Rod Anode Installation

Rod anodes can be supported by the cable from a clevis at the top of the gate. Since ice and debris are expected, the anodes need to be protected. This is best done by installing them within perforated polyethylene or fiberglass pipes. A steel half-pipe bumper is used outside the plastic pipe. The anodes may be secured at the bottom using a stabilizing weight or stand off device.

Other Gate Applications

Anode configurations for a Cordell Hull tainter gate and a Cape Canaveral sector gate are shown in Figures B7 and B8.

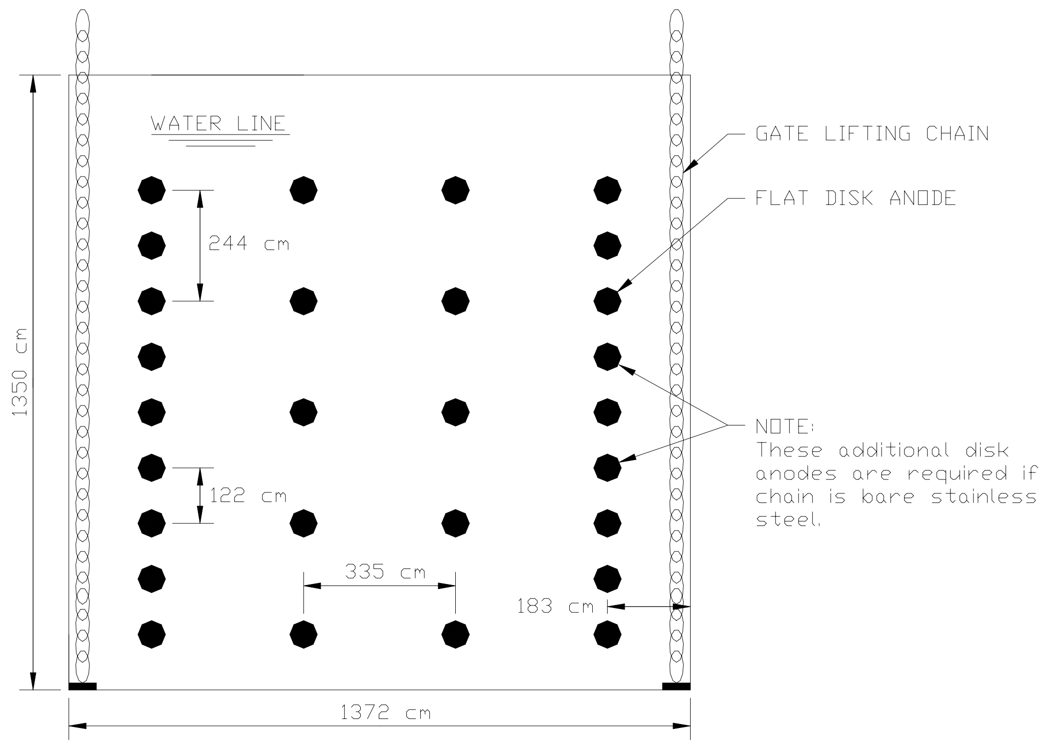

Figure B7. Tainter gate design at Cordell Hull showing flat disk anode placement

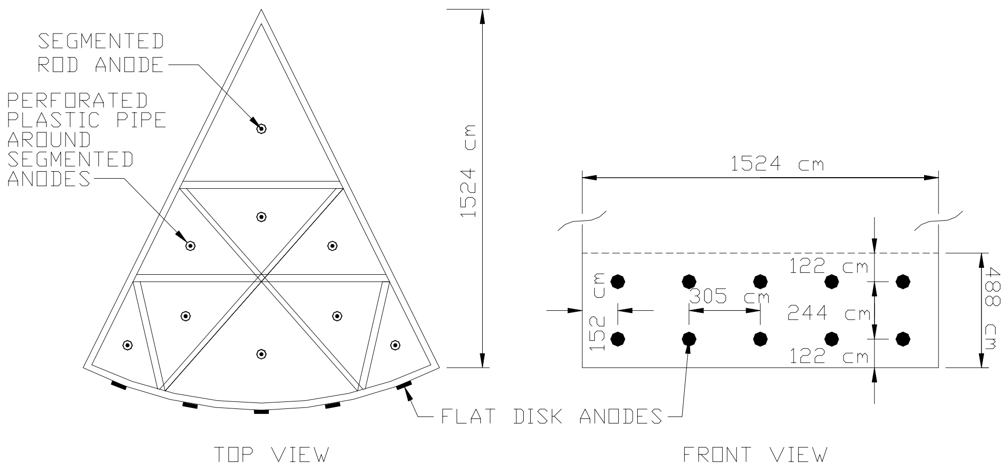

Figure B8. Sector gate design at Cape Canaveral showing flat disk anode placement